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During a Variable Demand Spatial Processing Task

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Brain activity, Measurement, Workload, Performance measures
Physiological measures, P300, Human performance, Task difficulty
Human operator, Human factors

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Topographical Analysis of Cortical Evoked Activity During a Variable Demand Spatial Processing Task

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This experiment studied changes in brain activity as subjects performed a variable demand spatial rotation task. The task involved the sequential presentation of a template histogram and a spatially rotated comparison histogram. Task difficulty was manipulated by varying the number of bars and the degree of rotation. Topographical analysis of the brain event-related activity data indicated the presence of negative components that were maximal at the vertex within 80 ms and bilaterally in the temporal lobes within 140 ms of stimulus onset and that appeared to be insensitive to changes in task difficulty. Demand-sensitive potentials were recorded, however. Positive components corresponding to P200 and P300 activity were recorded symmetrically around site Pz. The P200 component declined in amplitude, but showed no changes in latency as task demand increased. P300 activity declined in both amplitude and latency as the task became more difficult. Finally, a positive component was recorded over right central cortex approximately 490 ms after stimulus onset. This component declined in amplitude but increased in latency as task difficulty increased.

THE COGNITIVE DEMANDS placed upon the human operators of current U.S. Air Force systems can be quite high. Pilots, for example, are presented with a very large array of information that they must evaluate and use to make decisions while flying fast and, sometimes, close to the ground. In order to provide systems that are compatible with human cognitive processing capabilities we must have a better understanding of how the human brain processes information. One approach is to study the electrical activity of the human brain to learn as much as that activity can tell us about human cognition. This includes studying both the time

course and the spatial distribution of activity while the brain is processing cognitive information, making decisions based on this information and taking action. In order to gain an understanding of how increasing cognitive workload is managed by the brain, it is necessary to manipulate the difficulty level of the task performed by the subjects. Changes in brain activity can then be evaluated as the level of cognitive involvement changes as determined by the task demands.

Complex human performance, such as flying an airplane, involves many cognitive modes. One approach to advance our understanding of brain function during complex task performance is to study the various components of cognition in isolation. For example, in this study, a spatial task which required mentally rotating objects and making comparisons to images held in memory was used. This task is similar to some of the operations required when flying (e.g., mental calculation of vectors or targets) as well as performance in other complex tasks. Since cognitive workload is of interest, three levels of task difficulty were used in order to determine the nature of brain activity to the different levels.

In the realm of human information processing research, ensemble averaging of EEG records, which are time-locked to the presentation of stimuli, has been widely used and found to yield a number of event-related components which appear to index various aspects of stimulus processing and information evaluation (e.g., N100, P100, N200, P200, P300, and other late components). For example, the amplitude and latency of the N100 component are dependent upon such physical properties of stimulation as the size or intensity of the stimuli (20) while the P300 component is sensitive to factors such as stimulus relevance or expectancy during an ongoing task (4). Components occurring later than 500 ms after stimulus onset generally correlate with motor responses required by the task (10). The parameters necessary to elicit these phenomena as well as the effects of extrinsic or intrinsic manipulations on wave-

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form magnitude, onset, and duration have been well characterized (4,7,12,20,23,25).

EEG phenomena constitute a complex electrical field, distributed over the surface of the scalp. Computerized topographical mapping of these fields generally provides excellent characterization of total cortical electrical activity because it utilizes a large number of electrodes distributed fairly evenly over the surface of the scalp. Also, mapping allows ready visualization of the distribution, as well as any changes in the cortical activity. The determination of the probable generators of event-related potentials (ERP's) is complex. Descriptive maps of potentials and their reversals (sites of opposite polarity that occur as a result of source-sink relationships among contributing neural structures) are largely inadequate for this purpose. However, changes in the topographical distribution of these potentials can suggest alterations in the number and strength of neural contributors. Topographical mapping is thus considered by many to be the first step in generator specification (1-3,6,8,9,17,21,24,26).

In the present study, we used computer-assisted topographical mapping in conjunction with a non-biased reference to analyze the distribution of evoked fields (and their reversals) in response to a variable demand spatial processing task. Our purpose was to characterize the latency, amplitude and distribution of these electrical components and any changes that might occur in their properties as a function of increased mental effort. By quantifying changes in neural responses to variable levels of processing of spatial information, we hypothesized that these data would provide the foundation for comparisons of spatial cognitive processing both in the laboratory and in the cockpit during actual flight.

METHODS

Subjects

Nine male college students participated in the present study. All subjects were paid volunteers. The subjects were all strongly right-handed ($M = 82.6$) as assessed by the Edinburgh Handedness Inventory (22). Subjects' ages ranged from 21 to 34 years, mean 24.75 years.

Task

The behavioral task was designed to place differential demands upon information processing resources allocated for the manipulation and comparison of spatial information. Originally developed by Shingledecker (27) as a subtest of the "Criterion Task Set" to assess cognitive demand, the program generating the task was modified to provide a constant intertrial interval (rather than subject-paced) as well as triggers for ERP collection. The subjects were required to view a series of histograms on a monitor positioned at eye level approximately 90 cm from the eyes. Their task was to decide whether the second histogram in a set of two (the "comparison") was identical to the first (the "template") and respond via a response pad with the right index and middle fingers. Cognitive demands were manipulated by varying the number of bars in the histograms as well as the spatial orientation of the comparison. Each bar was

one of six possible heights and the height of each was varied for each template to provide a variety of stimuli. The low demand condition was defined as a two-bar template histogram followed by a comparison rotated 0°. The medium demand level was obtained by presenting four-bar templates followed by comparison histograms rotated either 90° or 270°. Finally, the high demand condition consisted of six-bar histograms followed by comparisons rotated 180°. All of the stimuli were white on a black background. Intensity of template and comparison histograms ranged from 38 to 42 ftL (Minolta Luminance Meter 1°) depending on stimulus width (22 mm, 50 mm, and 78 mm, respectively, for the low, medium, and high conditions).

All template items were presented for 1,000 ms. The duration of comparison histogram presentation was dependent upon the subject's reaction time. However, the maximum time allotted for a response was 1,500, 2,500, and 3,500, respectively for the low, medium, and high performance levels. Five hundred milliseconds separated template offset and comparison onset. New trials were presented 2,000 ms after the subject's behavioral response or comparison stimulus offset. There were 50 template-comparison items randomly presented during each difficulty condition, 25 matches and 25 non-matches.

The subjects were trained on all three levels of the behavioral task until they reached a criterion of 90% correct responses. Criterion performance was generally reached within two 1-h sessions.

Procedure

Upon completion of training, a 2-h experimental session was scheduled. At this time, subjects were fitted with a nylon cap containing 21 tin electrodes (Electro-Cap International) positioned in accord with the International 10-20 System (see Fig. 1 for illustration of electrode sites). FPZ served as the ground while the remaining 20 electrodes were designated as active recording sites. In addition, two electrodes were attached to the mandibles to act as reference sites. The subjects were then placed individually in a sound-attenuated, electrically shielded chamber under dimly lit conditions and asked to fixate on the center of the monitor screen. Subjects were monitored by camera to assess compliance with instructions.

ERP's were recorded on a topographical mapping system (Bio-Logic Brain Atlas) and averaged across the 50 template-comparison presentations for each task condition. Because our primary intent was to describe the general neuronal activity associated with spatial processing, matched and unmatched trials (as well as correct and mistaken responses) were averaged together in order to yield more noise-free ERP averages. The brain potentials were band-passed filtered from 0.1 to 30 Hz. Amplifier gains were preset at 30,000 and artifact rejection was automated (i.e., the system deleted any data segments exceeding 95% of the analog to digital range). All electrode impedances were 3 kΩ or less. Sampling was externally triggered via the stimulus computer exactly 152 ms prior to the video-synched comparison histogram onset. Sampling rate for the low

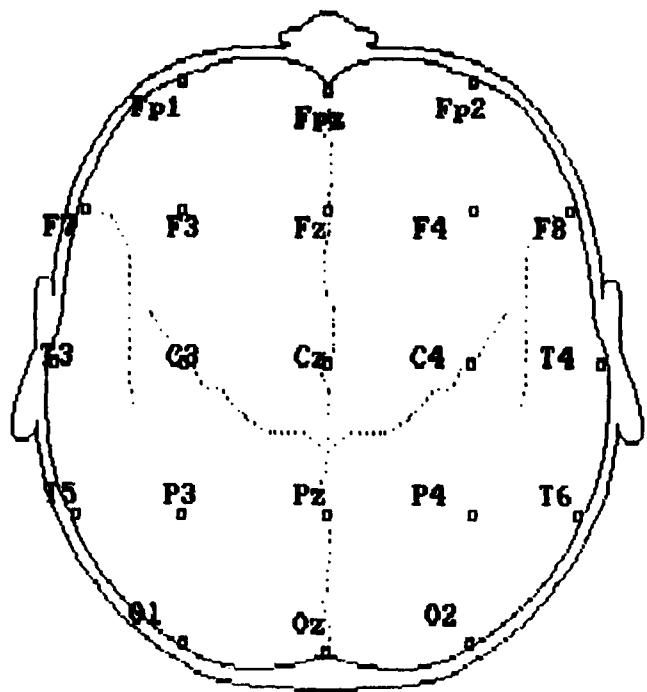


Fig. 1. Schematic of head (dorsal view) showing individual electrode sites.

condition was 250 Hz, while the rate for both the medium and high conditions was 125 Hz. Epoch durations were 1,024 ms for the low performance level and 2,048 ms for the medium and high conditions. The different sampling rates and epoch durations were necessary due to conflicting restraints between the CTS task (trial rate) and the Bio-Logic sampling routines (limited to 256 data points). The two sampling rates were equilibrated by converting the 250-Hz sample to the 125-Hz rate by averaging adjacent data points together to yield the missing data points of the larger epoch file (Brain Utilities). The temporal sequence of difficulty level presentations was randomly determined and each level was presented twice within a session. Resulting topographic fields were then averaged across the two presentations.

Analysis

Temporal and waveform distortions of ERP's due to reference electrode location are an inherent problem in many studies (13–16). Such recording artifacts can distort the distribution of the event-related electrical field. Therefore, in the present study, an essentially reference-free distribution of the brain potentials was computed using the source derivation method developed by Hjorth (13–15). The source derivation applies a Laplacian operator to the ERP's to compute the relative contribution of potentials from radial electrodes on the site of interest. Signal referencing in this manner provides better localization of cortical foci, attenuates low spatial frequency activity in the ERP data, and may provide better estimates of component latency (18). The Laplacian values represent current density and are expressed as microvolts per centimeter squared ($\mu\text{V}/\text{cm}^2$).

Latencies and amplitudes of event related potentials to the comparison histograms were determined via a

peak-picking program (Brain Utilities). All values were then analyzed by an SAS analysis of variance (ANOVA) program using electrode site, evoked component, and performance level as repeated measures factors.

RESULTS

Reaction Time

The mean reaction times for the low, medium, and high conditions were 580, 810, and 867 ms, respectively. An analysis of variance indicated that these differences were highly significant [$F(2,16) = 26.04$, $p < 0.0001$]. Subsequent main effects tests, however, indicated that only the low demand level reaction times were significantly faster than the medium and high conditions (Duncan $df = 16$, $p < 0.05$). Although the mean reaction time for the high demand condition was 57.5 ms longer than the medium condition, this difference failed to reach significance.

Event Related Brain Activity

Video camera monitoring of subjects in the present study revealed minimal movement of facial musculature. Consequently, artifact rejection of the ERP data was low (4.0, 6.9, and 8.3 trials on the average for the low, medium, and high conditions). An ANOVA of the mean rejection rate by subject and difficulty level indicated no significant differences.

Inspection of the topographical maps revealed a high degree of similarity in cortical activity across subjects within each performance level. Statistical verification of observations made from the maps was accomplished in the following manner. For each subject, visual inspection of the electrical waveforms across the 20 active recording sites indicated that only five event-related components could be reliably observed in the three task conditions; specifically, N80, N140, P200, P300, and P490 waveform components. An N200 event-related component was also observed. However, the appearance of this component was not reliable or consistent across subjects and conditions. This component was, therefore, eliminated from further examination in the present study. The peak amplitudes and latencies of the five reliable components were determined via the pick-peaking software package using time windows of 70–150 ms for both the N80 and N140, 170–230 ms for the P200, 270–360 ms for the P300, and 380–700 ms for the P490. The grand mean and standard deviation (SD) for the amplitudes ($\text{in } \mu\text{V}/\text{cm}^2$) were then calculated for each component and only those electrode sites with peak amplitudes greater than 1 SD away from the mean were selected for further statistical analysis. This procedure yielded one site for the N80 (CZ), two relevant sites for the N140 (T5 and T6), three sites for the P200 (P3, P4, and Pz), three sites for the P300 (P3, P4, and Pz), and one site for the P490 (C4).

Fig. 2a shows a topographical map displaying a negative event-related component that peaked (maximum amplitude) at site CZ at approximately 80 ms (N80) after stimulus presentation. From Fig. 2b, it can also be seen that negative evoked activity was evident at sites T5 and T6. T6 showed the largest negativity. Unlike the wave-

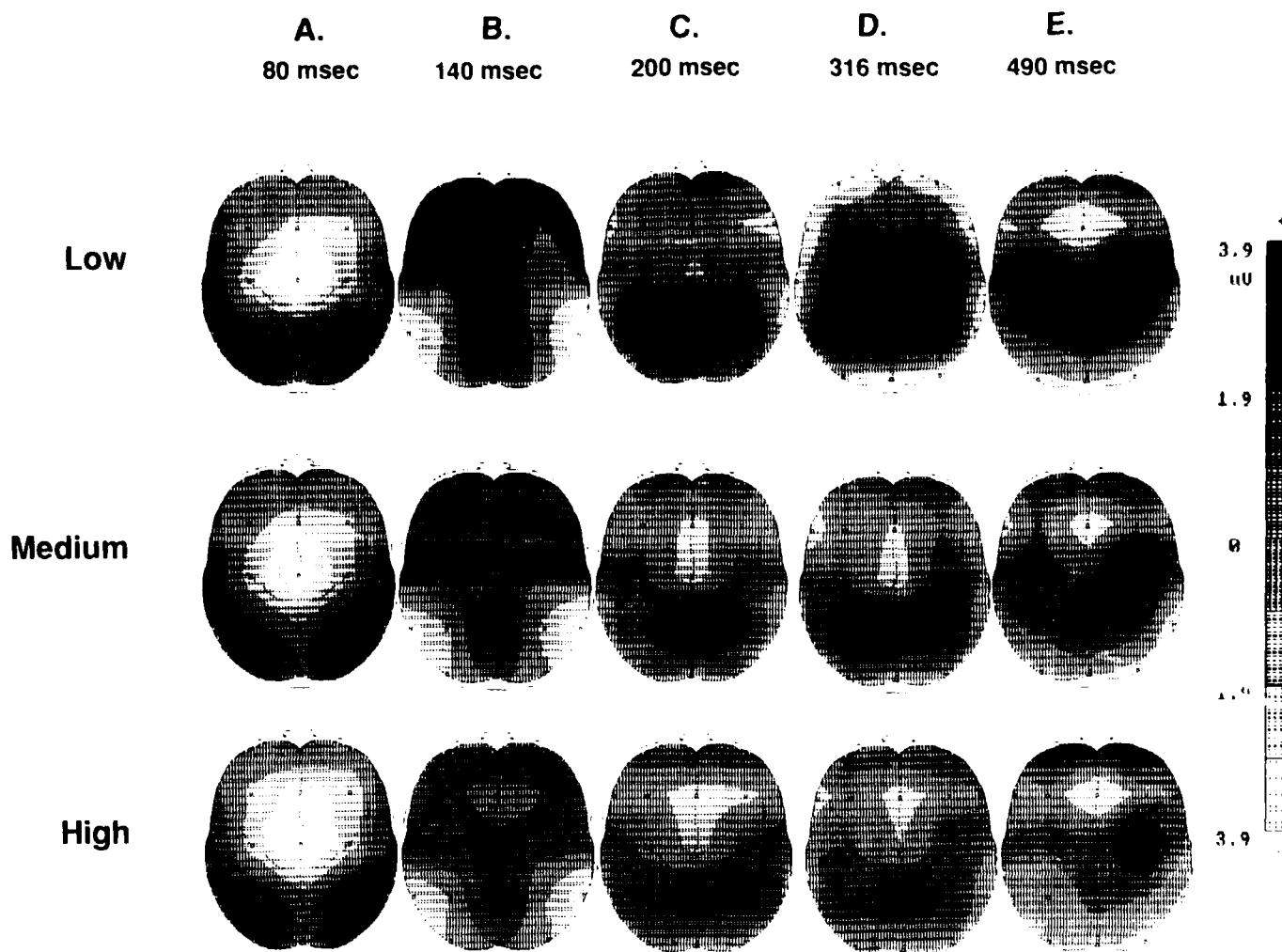


Fig. 2. Topographical maps displaying the distribution of electrical activity (grand average) during the three difficulty conditions. Negative potentials are evident at CZ approximately 80 ms (A), and at T5 and T6 approximately 140 ms (B) after stimulus presentation. Positive potentials can be observed at P3, PZ, and P4 approximately 200 ms (C), and at P3, PZ, and P4 approximately 316 ms (D), and at C4 approximately 490 ms (E) after stimulus onset.

form at CZ, these two negativities appeared approximately 140 ms (N140) after stimulus onset. All three waveforms remained relatively stable in amplitude with each increase in task demand. A repeated measures ANOVA indicated no significant differences in amplitudes of either the N80 or 140 components across electrode sites, by difficulty levels or resulting from the interaction. Separate ANOVA's of the N80 and N140 latencies indicated a significant main effect for difficulty level [$F(2,16) = 8.31, p < 0.0033$ and $F(2,16) = 4.48, p < 0.0284$, respectively]. Duncan tests of these main effects indicated that N80 and N140 latencies in the low condition were significantly longer than those occurring in either the medium or high conditions ($df = 16, p < 0.05$ for both tests). No significant differences were observed between the latencies of components occurring in the medium and high levels.

Inspection of the total electrical field indicated that N80 reversals (i.e., waveforms of opposite polarity, equivalent latency, and comparable amplitude) were located maximally at T5 and T6, and to a lesser extent at P3, P4, O1, and O2. N140 reversals were observed more anteriorly at CZ, F3, FZ, and F4.

Fig. 2c shows a cortical map slightly later in time. It

is clear from this map that there was positive event-related activity centered at the PZ electrode with lower levels of activity associated with the P3 and P4 sites at approximately 200 ms following 'comparison' onset. As cognitive demand increased, both the amplitude and latency of the activity associated with the PZ site decreased. In the high demand condition, the activity associated with site PZ was approximately $2.64 \mu\text{V}/\text{cm}^2$ less than in the low condition and occurred on the average 11 ms earlier. P3 and P4 remained largely unaffected by increases in task demand. An ANOVA of the amplitude values indicated a significant electrode site by difficulty level interaction [$F(4,32) = 3.90, p < 0.0108$]. Post hoc analyses indicated that this effect was limited to a decrement in amplitude of the PZ potential from the low to high demand conditions [$F(2,16) = 10.98, p < 0.01$]. An ANOVA of the P200 latencies failed to indicate any significant changes across difficulty levels. Amplitude and latency data for the P200 are depicted in Fig. 3. Opposite polarity responses of comparable latency to the P200 activity observed at the three sites (P3, P4, and PZ) were noted in a number of anterior locations including FP1, F7, F4, T3, CZ, and T4.

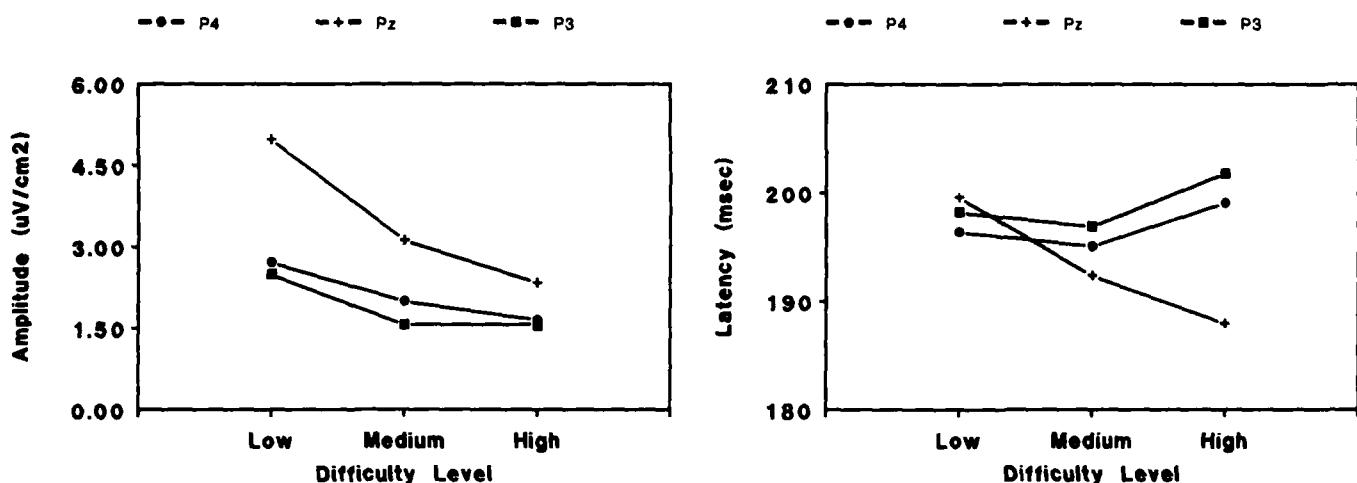
A.**B.**

Fig. 3. P200: (A) The peak amplitude ($\mu\text{V}/\text{cm}^2$) of the P200 ERP plotted as a function of scalp site and task difficulty. Only the potential recorded at the PZ site declined significantly in amplitude from the low to high difficulty conditions. (B) The peak latency of the P200 ERP plotted as a function of scalp site and task difficulty. No significant differences were found.

Larger positive components are evident at sites P3, P4, and PZ in Fig. 2d. These peaks appeared approximately 316 ms after stimulus presentation and showed the largest positivity at the PZ electrode. Fig. 4 indicates that the P3, P4, and PZ potentials showed a decrement in both amplitude and latency with increasing task difficulty, with the PZ electrode showing the largest decrement in amplitude (approximately $3.1 \mu\text{V}/\text{cm}^2$) and the P4 site, the largest decrement in peak latency (approximately 18 ms). Analysis of variance indicated significant main effects for electrode site [$F(2,16) = 9.87, p < 0.0016$], difficulty level [$F(2,16) = 45.71, p <$

0.0001] and the interaction of site by difficulty [$F(4,32) = 3.60, p < 0.0156$]. It was subsequently verified that the largest component was recorded at PZ (Duncan $df = 16, p < 0.05$). Post hoc simple main effect tests indicated that all of the selected electrodes declined in amplitude across the demand levels [$F(2,16) = 8.76, p < 0.01$ for P3; $F(2,16) = 10.4, p < 0.01$ for P4; $F(2,16) = 30.72, p < 0.001$ for PZ]. An ANOVA of the P300 latencies indicated that only the main effect for site was significant [$F(2,16) = 4.96, p < 0.021$]. The peak latency at PZ occurred earlier than those at the other electrode sites (Duncan $df = 16, p < 0.05$). Further-

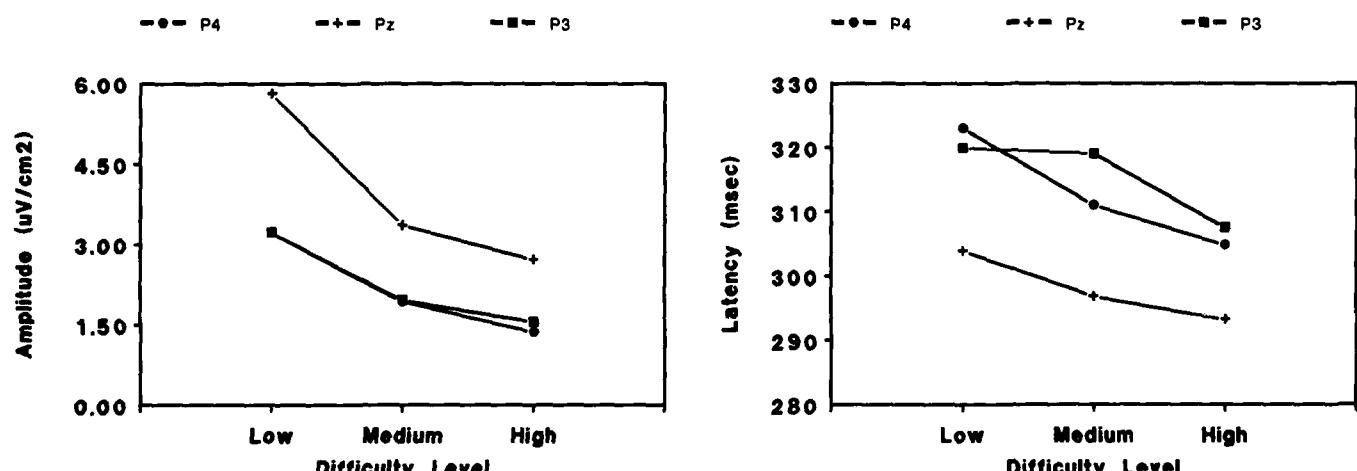
A.**B.**

Fig. 4. P300: (A) The peak amplitude ($\mu\text{V}/\text{cm}^2$) of the P300 component plotted as a function of scalp site and task difficulty. Statistically, a significant decline in voltage was observed at all three sites. (B) The peak latency of the P300 plotted as a function of scalp site and task difficulty. The latencies observed in the low condition were significantly longer than those in the high workload condition.

more, the peak latency of the potentials observed in the low demand level were significantly longer than those observed in the high condition (Duncan $df = 16$, $p < 0.05$). P300 reversals were scattered diffusely throughout the total electrical field. Sites of reversal included FP1, FPZ, FP2, F7, F8, T3, T4, O1, OZ, and O2.

Late positive activity, designed as P490, was localized predominantly over site C4 in the right hemisphere approximately 490 ms after stimuli presentation (see Fig. 2e). Fig. 5 shows that, like the P200 and P300 components, the P490 activity also declined in amplitude as task difficulty increased [$F(2,16) = 3.43$, $p < 0.057$]. From Fig. 5 it can also be seen that the effect of task difficulty on the latency of this activity was considerable, resulting in a 162-ms increment in peak latency from the low to high conditions [$F(2,16) = 4.44$, $p < 0.0292$]. A Duncan's test indicated that this effect was due to the difference between the low and high conditions only ($df = 16$, $p < 0.05$).

Reversals at FZ and CZ were of shorter duration than the P490 observed at C4. However, the peak latencies of the waveforms at these sites coincided with the peak latencies of the P490 potential across the difficulty levels.

DISCUSSION

In the present experiment, we were interested in identifying changes in brain event-related activity associated with variable demand cognitive processing of spatial information. Behaviorally, only two levels of difficulty could be substantiated in the present study. This result is perplexing in that others have successfully observed three demand levels using this task when the intertrial interval was response-dependent (19,27). Neurophysiologically, the results of the brain activity analyses were found to closely parallel the behavioral findings. All of

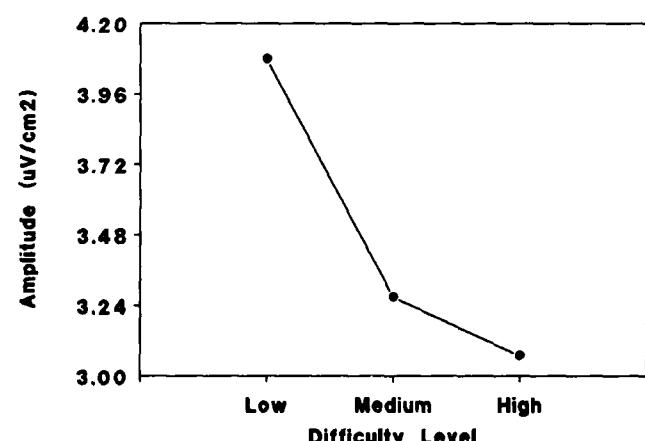
the components which were sensitive to difficulty manipulations (i.e., showed changes in amplitude and latency across conditions) either differed significantly from the low to medium or low to high conditions. No significant differences were observed between the medium and high levels. The consistency between performance and the brain activity findings suggests that the version of the spatial task used in the present study, in fact, had only two levels of cognitive effort or that subjects participating in the present experiment were not representative of earlier samples. In either case, the results indicate a strong correspondence between behavior and scalp electrical potentials.

In the present study, using visual stimuli, negative components were consistently observed at the CZ electrode site within 80 ms of comparison stimulus presentation and bilaterally at sites T5 and T6 within 140 ms. The topographical and temporal disparity between activity at these sites suggests that two distinct ERP phenomena were being generated. That N80 and N140 reversals of activity were observed in distinct topographical zones supports this claim.

Increasing task difficulty appeared to have little effect on the properties of the N80 and N140 waveforms. None of these components showed any diminution in amplitude across demand levels. Overall, the results of the analyses suggest that the N80 and N140 observed in the present study were stimulus-bound rather than indices of cognitive effort. Similar conclusions have been forwarded by researchers using a variety of tasks (1,2).

P200 activity was observed over the parietal areas P3, P4, and PZ. It is possible that the waveforms seen at the individual sites represent fundamentally different components as task difficulty was found to affect the activity at these sites differently. Activity at PZ significantly declined from the low to high difficulty conditions while

A.



B.

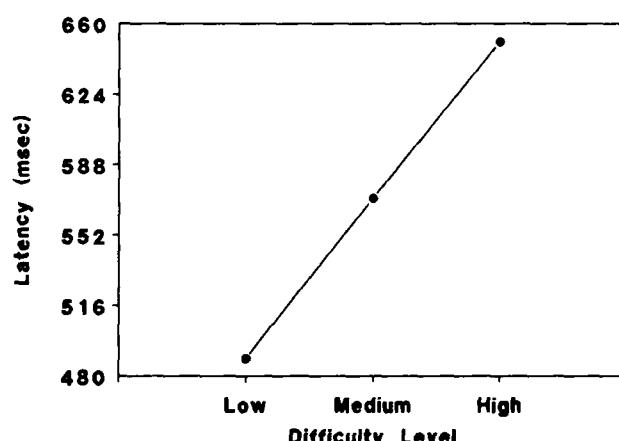


Fig. 5. P490. (A) The peak amplitude ($\mu\text{V}/\text{cm}^2$) of the P490 at site C4 plotted as a function of task difficulty. Significant differences were found between the amplitude of the component during the low and high conditions. (B) The peak latency of the P490 at site C4 plotted as a function of task difficulty. Statistically, increased demand produced a dramatic increment in the latency of this event-related component.

P3 and P4 were unaffected. Also, while the overall latency ANOVA was not significant (thus, no post-hoc tests were performed), the PZ P200 declined by 11 ms with increasing task difficulty. Activity at the P3 and P4 sites remained largely unchanged. Because of the relative insensitivity of activity at the P3 and P4 sites, we suggest that the PZ P200 is sensitive to cognitive loading and that the P3 and P4 components are indexing some aspect of the physical stimulation.

P200 reversals were found at a number of frontal sites. The latencies and durations of the P200 activity at P3, P4, and PZ were similar to such an extent that differentiating between reversals on that basis was impossible.

Donchin and Wickens (5) state that the P300 component of the human event-related potential is sensitive to cognitive load. In the current experiment, we identified evoked P300 activity that evidenced such a sensitivity. This activity was located predominantly over parietal cortex (P3, P4, and PZ) with the largest positivity occurring on the midline (PZ). It is possible that the waveforms observed at P3 and P4 were conducted from the PZ site, as they were consistently lower in amplitude and a few milliseconds later in time than the PZ potential. Similar magnitudes of decline in both amplitude and latency of the P300 were observed from the low to high conditions across the three parietal sites.

Like the P200 activity, P300 reversals were scattered diffusely through frontal cortex. Reversals, however, were also observed in temporal and occipital cortices. Such widely dispersed reversals suggest that multiple sources probably contribute to this component.

Traditionally, increased ERP latencies have been noted in response to increasing task difficulty and declines in ERP latencies have been associated with increasing stimulus intensity, size, etc. (4,5). The present study found declining P200 and P300 peak latencies concomitant with increased task difficulty. We can offer several viable hypotheses for these findings, but any definitive statement must await further testing. For example, it could be hypothesized that the latency decline reflected the 4 ftL increase in stimulus intensity associated with the six-bar histograms, rather than a "workload" effect. Such an argument is tempered, however, when one considers that only the ambient light level of the display changed. Individual bars on the histogram did not change in intensity. Alternatively, it might be suggested that the declining latencies reflect decreased activation of the brain by the task. This alternative also seems unlikely. Subjective reports by the subjects, as well as their reaction times, indicated that the medium and high difficulty tasks were more challenging than the low condition. Also, determined efforts were made to prevent fatigue/boredom (possible contributors to inattention) by permitting frequent rest breaks during testing and randomizing the order of task presentation. These hypotheses await further testing.

Additional activity, corresponding to the P490, was located in the right hemisphere over site C4. The P490 reported in this study might be better described as a broad, large amplitude slow wave. Like the P200 and P300, the P490 component diminished in amplitude as

task difficulty increased. The peak latency, however, increased concomitantly with the demand level. The shape of this waveform differs substantially from a "typical motor potential" as described by Goff et al. (10). In addition, because the peak of this ERP was always found to precede the subjects' reaction times and was found over the right hemisphere of our dominantly right-handed subjects, it can be posited that it is more closely correlated with cognitive evaluation than motor performance.

None of the 21 sites recorded in this study exhibited a reversal that shared the same characteristics as the P490. However, sites FZ and CZ showed shorter duration reversals which peaked at approximately the same time as the C4 P490.

In the present study, similar results were obtained for amplitude measures of P200, P300, and P490 activity. However, only one component, the P490, exhibited a delayed peak response as the task became more difficult. It may be that this component is specific for spatial processing and is an indicator of the right hemisphere engagement to be expected during such a task. Further experimentation is necessary to determine if this component is a generalized phenomenon occurring in other complex tasks and whether fundamentally different tasks such as linguistic or mathematical processing would produce a different distribution of components over other cortical areas, as well as the changes in amplitude and latency observed as a function of cognitive demand in the present experiment.

The results of the present study quantify the topographical distribution of event-related brain activity elicited by a spatial processing task, as well as the changes wrought in these components as a function of increasing cognitive demand. This approach to understanding human cognitive activity provides information about both the time course and topographical location of brain activity involved in a particular task. This permits one to speculate about the nature of the cognitive components of a task and also provides information about the functioning of different brain areas. By increasing the database, it will be possible to determine the temporal and spatial aspects of brain activity during many different types of cognitive processing. A similar approach, using ongoing EEG analysis and a verbal memory task by Gundel and Wilson (11), demonstrated reduced occipital and parietal alpha and increased theta activity in left frontal sites as the memory load increased. These studies demonstrate that it is possible to measure brain activity and determine the nature of the ongoing cognitive processing. This would be very useful in many applied situations such as flying and design evaluation.

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